Innovations and Trends in Reclamation of Metal-Mine Tailings in Washington

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INTRODUCTION

Tailings are mine mill waste products consisting of ground rock from which the valuable minerals have been extracted. Due to inherent chemical and slope instability and other potential environmental problems, they can represent long-term public and private land-management challenges. For example, precious metal tailings may contain dissolved metals and cyanide complexes (Miller, 1997). If the tailings impoundment is poorly designed, constructed, or reclaimed or is breached or otherwise loses its integrity, release of contaminants and sediments can threaten the environment. In response to these potential problems, state and federal agencies and local government have steadily increased environmental scrutiny and regulation of metal mine tailings since the early 1970s.

Modern tailings impoundments that are properly designed, sited, constructed, maintained, and reclaimed are unlikely to cause acute environmental problems. At many metal mine sites, the single most important environmental issue is the quality of reclamation of all the mine's components, including waste rock dumps, the mine itself, and the tailings facility. There can be no high-quality reclamation without considering all aspects of a tailings facility.

TAILINGS CHARACTERISTICS

Tailings are generally composed of fine sand- or silt-size particles, typically deposited as a slurry, and, depending upon the method of deposition, may be graded so that coarser material is nearer the point of discharge. Gradients in grain size occur both vertically and horizontally.

At most mines, some of the metals in the mined material cannot be recovered in the mill and are discharged to a tailings disposal facility (TDF). In older tailings or where gangue metals are not economic, the metal content can be 10 percent or higher due to milling inefficiency. Many modern mining operations achieve metal concentrations of less than 1 percent in tailings (Williamson and others, 1982). However, at some mines, it is not the metal with economic value that is problematic, rather it is the associated metals that reach toxic levels.

Due to variations in milling, original mineralogy, and deposition method, tailings can have high salt contents, be acid or alkaline, have macronutrient deficiencies, display particle-size stratification, and lack organic matter (Munshower, 1994). Other sources of toxicity are processing agents, catalysts, reagents, and chemicals that are not recovered in the mill and thus are discharged to the TDF. Cyanide is the most toxic reagent commonly used in metal recovery, but it degrades quickly when exposed to air. At most modern mine operations, tailings are routed through a cyanide destruction and detoxification circuit before discharge to the TDF. Cyanide destruction methods, which can also be toxic, are discussed in Denton and others (1992), Smith and Mudder (1991), and Norman and Raforth (1995).

To minimize toxicity of tailings, mine planners must consider original rock chemistry, including metal and sulfide content, in reclamation. In addition, revegetation success on tailings is influenced by chemical and physical changes introduced by the milling process.

LOCATION AND CONSTRUCTION OF TAILINGS IMPOUNDMENTS

Because the ultimate success of tailings containment and isolation depends on the long-term stability of the impoundment dam itself, a description of impoundment types is warranted. Tailings impoundments (dams) can be broadly classified as follows:

- valley containment, where a dam is constructed across the valley,
- level ground impoundment, with ring dike containment and tailings deposited in the center,
- sidehill impoundment, which relies on a dam constructed with three sides.

The rugged topography in Washington metals mining districts generally dictates that the impoundment design be either valley or sidehill containment (Fig. 1). Currently, mining companies tend to use mine waste material for impoundment construction. Waste rock can be used for the main portion of the embankment if the rock is of suitable construction quality and will not generate acid rock drainage. Clean sand and gravel, if available from the overburden, has also been used. Generally, the embankment is constructed in 2- to 8-ft-thick lifts and compacted. Some mine operations outside of Washington use cyclones (cone-shaped devices that have no moving parts) to separate the coarse fraction from the fines by centrifugal force; the sediment is discharged at relatively low moisture content through the bottom. The coarse sands can then be stacked to form the sand portion of various embankment types. The overflow, or fines, is discharged to the tailings pool away from the sand embankment.

Most tailings dams in Washington are low-permeability water-retaining structures. Tailings dams that can impound 10 acre-feet or more of water measured from the dam crest must meet state dam safety standards. The Washington Department of Ecology's Dam Safety Section regulates planning and construction of dams under Revised Code of Washington (RCW) 90.03 (The Water Code) and RCW 86.16 (The Flood Control Act).

TDF dams are generally constructed using the downstream, centerline, modified centerline, or upstream method (Fig. 2). The downstream method requires the most material, covers the

Figure 1. Echo Bay Minerals Co. (Republic, Wash.) constructed this sidehill tailings impoundment that includes a geosynthetic liner with an underdrain system. The impoundment footprint is approximately 91 acres, and the surface area of the tailings is 61 acres. The maximum height of the embankment is 115 ft. The company used a centerline method for dam construction.

largest area, and is the most expensive to build. Figure 3 shows a completed downstream method TDF. The downstream method results in TDFs that are generally more stable than dams constructed using other methods, and the integrity of any geomembrane (low-permeability synthetic) liner can be easily maintained. Costs for the downstream construction method may be reduced if suitable material is available on the mine site. In areas that may be subjected to large seismic events, the downstream method is the most stable. The upstream method uses the tailings as its base as each lift is added. It is the least expensive to build and the least stable (Gipson, 1998). The centerline method shares both advantages and disadvantages of upstream and downstream methods.

Construction methods can affect tailings discharge management. Valley or side valley containment is more effective than stacking tailings on level ground. Discharge from a valley containment system is normally confined to one point, and seepage is fairly easy to collect. Reclamation of a valley-contained TDF is simpler than for a ring dike TDF because long-term surface drainage can be more readily re-established (Welch and Firlotte, 1989).

TAILINGS SITE SELECTION

Site selection for an impoundment must take into consideration the position of ore bodies, distance and elevation from the mill, watershed characteristics, existing and future land uses, site geology, environmental concerns (such as water quality, dust control, vegetation, and wildlife), property ownership, proposed type of closure and reclamation, and the overall costs of the project. In Washington, the siting criteria for tailings impoundments are set forth in the Metal Mining and Milling Act (RCW 78.56.090). The mining company may propose several sites, or the Department of Ecology may select a site. The Department of Ecology must issue a site selection report for the agency's preferred location for the TDF. The report must analyze the feasibility of reclaiming and stabilizing the tailings; it must also take into account the objectives of the mine proponent's application relative to mining and milling operations. RCW 78.56.090 states "these objectives shall consist of, but not limited to (a) operational feasibility, (b) compatibility with optimum tailings placement methods, (c) adequate volume capacity, (d) availability of construction material, and (e) optimized embankment volume." Siting criteria are qualitatively based on proximity to the 100-year flood plain and surface and ground water, topographic setting, geologic hazards such as landslides and active faults, visual impacts, soil, geotechnical, and hydrologic characteristics.

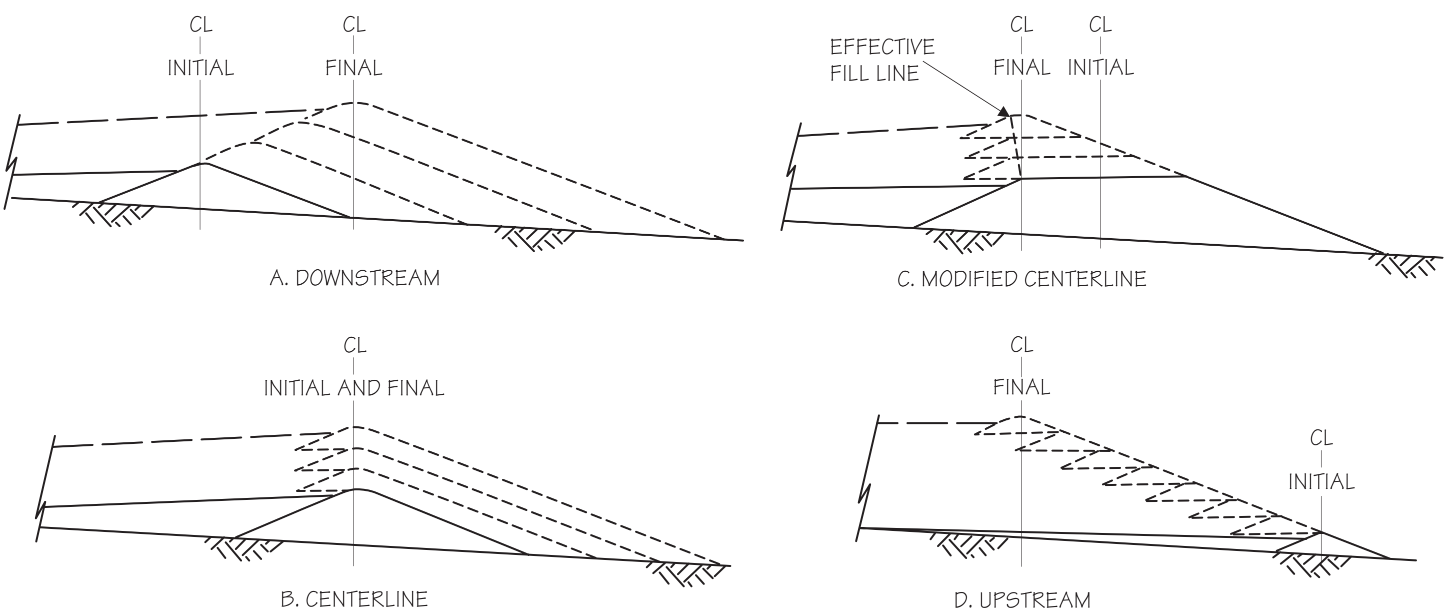

Figure 2. Cross sections of four types of tailings dam embankments. CL, centerline.

LINERS

A liner system helps minimize the chances of leakage from the tailings into ground water or surface water. Historically, liners (soils, clays, and geomembranes) have failed and leaked, but recent advances have made liners far more reliable. Mine location, environmental considerations, and state laws or regulations help determine the type of liner to be used in tailings facility construction. Further, liner design must be based on the assumption that leaks will occur and that leak detection and recovery systems are necessary.

If a site lacks adequate natural materials such as clay, sand, and gravel to construct liner components, a synthetic liner system must be used. Typically, multiple liners are required, and the bottom layer consists of clay or amended soil material. Nonetheless, the mining company, agencies, and third party consultants should regularly conduct careful reviews of construction quality assurance/quality control (QA/QC) (Norman and Raforth, 1995).

Figure 3. Tailings impoundment and dam at the Cannon mine (Wenatchee, Wash.) during reclamation in 1996. The impoundment is about 35 acres. The dam face is 250 ft high and 1,000 ft long and extends completely across the Dry Gulch valley. The downstream dam method was used. Dam materials are mostly basalt and mine waste; a clay core reduces permeability.

Important considerations in choosing material for soil liners are availability and composition. In general, increasing the clay content of the liner material decreases the permeability. The liner material must have an appropriate amount and type of clay to achieve low permeability, high plasticity, and chemical stability when in contact with the tailings, which may contain cyanide, metals, acids, or other reactive solutions. Material for soil liners can consist of on-site or local borrow materials (if they have the correct clay content), bentonite, or mixtures of both. Imperfections such as roots must be removed during construction of the liner system.

The thickness and method of liner compaction are engineering considerations. Most clay liners are designed to achieve a hydraulic conductivity (permeability) in the range of 10^{-6} to 10^{-7} cm/sec (1.0 to 0.1 ft/yr). To attain low-permeability containment, clay liners must be thoroughly mixed, conditioned, carefully placed, and properly compacted, as well as protected against damage to continuity due to cracking from drying and shrinking (Hutchison and Ellison, 1992). Expandable clays (smectite and illite-smectite group clays) are less permeable than other clays (kaolinite or illite) and are more commonly used.

Impoundments have used synthetic liners since the 1940s. Technological advances in the manufacture of synthetic materials during the past decade have resulted in the widespread use of geomembranes for all components of the liner system (Ellison and others, 1992). Geomembranes are made of polyvinyl chloride (PVC), Hypalon™, high-density polyethylene (HDPE), very low density polyethylene (VLDPE), chlorinated polyethylene (CPE), asphalt/hydraulic asphaltic concrete (HAC) (Dorey and others, 1988), and XR-5 (chlorosulfinated polyethylene) (Marcus, 1997). The three most commonly used geomembranes are HDPE, PVC and VLDPE.

Geosynthetic clay liners (GCLs) are also commonly used. GCLs sandwich bentonite (composed mostly of smectite-group clay) between two geotextiles (woven or non-woven permeable synthetic fabrics) that are glued or sewn together. These liners have been used for the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA) containment systems and covers for uranium mine tailings since 1988. They have the advantage of being easily placed, can be less costly than imported clays (if local clays are not available), and are tolerant of handling during installation. A drawback of GCLs is the loss of shear strength stability when they become hydrated and the potential for significant increase in permeability because of the high cation-exchange capacity of the bentonite (Richardson, 1994).

Important considerations in choosing geomembranes are thickness, strength, durability, cost, cover material needed for cushioning, the method of placement, and the construction method and quality of seams between the sections of the liner. The suitability of a geotextile material varies with the density achieved during manufacture (Ellison and others, 1992). In addition, geomembranes should not react with the reagents used in the milling process or in the tailings. The long-term life expectancy of geomembrane liners currently in use is not known but is shortened by exposure to sunlight. Most geomembranes are now manufactured with ultraviolet inhibitors and are expected to last more than 50 years even if exposed to sunlight.

In the past, tailings from mills using flotation-only circuits were deposited in unlined facilities. The mine operators relied on the perceived "relatively benign" nature and the low permeability of the tailings to minimize ground-water impacts (van Zyl, 1997). However, reliance upon these characteristics alone is not adequate to meet current water-quality protection requirements, which is another reason liners are required.

Water quality can be severely degraded if liners fail. Past failures of geomembrane liners have been attributed to poor welding of the seams or joints in the geomembrane or to puncturing during or after placement. Properly cushioning the geomembrane can prevent punctures. New techniques for welding seams have considerably improved seam reliability. Installing a cover layer to cushion and protect the geomembrane has also been key in successful operations. Indeed, most failures can be prevented by strict adherence to QA/QC during pad construction (Hutchison and Ellison, 1992).

Geotextiles are used above and below the geomembrane layer to protect against penetrations by underlying rocks or large particles due to loads from construction activities or the weight of the waste material. Protecting and cushioning the liner can be accomplished with clay- to sand-size material. Small rounded gravel has also been used successfully to protect geomembranes from puncture. The protective soil must be relatively free of large rocks and roots that could concentrate stress on the liner.

The preceding discussion indicates that liners must be designed on a site-specific basis. Common designs in use today consist of:

- two layers of synthetic material separated by a permeable leak-detection layer (sand or a permeable synthetic net);
- a lower layer of clay or clay-amended soil, a middle leak-detection layer of sand, and a capping synthetic layer; and
- a composite liner composed of a synthetic layer immediately overlying a clay or clay-amended soil layer.

REQUIREMENTS FOR TAILINGS FACILITIES IN WASHINGTON

In Washington, RCW 78.56 (Metals Mining and Milling Act) requires that tailings facilities be designed and operated to prevent the release of pollutants. Mine operators must apply "all known available and reasonable technology" to limit the concentration of potentially toxic materials in a tailings facility and to assure protection of wildlife and human health.

Tailings facilities must have a containment system that includes an engineered liner system, leak detection and collection elements, and a seepage collection impoundment to assure that a leak of any substance regulated under RCW 90.48 (Water Pollution Control Act) will be detected before escaping to ground or surface water. The design and management of the facility must ensure that any leaks are detected in a manner that allows for remediation pursuant to RCW 90.48.

Also according to RCW 78.56, applicants for metal mines and tailings facilities permits must submit a detailed engineering report about the facility design and construction to the Department of Ecology for review. If a dam is included, the Department of Ecology's Dam Safety Section approves the design and construction, while the Water Quality Section approves the waste treatment system. Tailings facility design must take into account natural conditions, such as precipitation and depth to ground water, but not as a replacement for the protection required by the engineered liner system.

The goal is to reduce the toxicity of mine or mill tailings and the potential for long-term release of regulated substances to the greatest extent practicable through stabilizing, removing, or reusing the substances. When the tailings facility is closed, isolation and containment of potentially toxic materials is assured.

Drainage Layers

Drainage layers must be included as part of the engineered liner system required by RCW 78.56. Drainage layers are intended to maintain a low hydraulic head above the liner acting as the containment barrier. Traditionally, high-permeability sand or rounded-gravel drain layers on top of the liner drain fluid transmitted through or expelled from the low-permeability tailings to a collection pond for treatment, if needed. Several inches of free draining gravel and coarse sand are adequate in most places to rapidly remove the small volumes of fluid. However, mining companies generally place thicker (8–18 in.) layers of sand and gravel for the drain layer. The sand drainage layer is generally placed between an upper geomembrane layer and a lower geotextile layer that is intended to minimize clogging of the sand by the fine tailings. The drainage layer commonly includes a network of closely spaced perforated pipes that rapidly drain collected fluids and minimize hydraulic head above the liner.

Geonets (a net-like synthetic) have also been used as drainage layers within liner systems and allow effluent to be collected at a single point. Geonets are formed with a minimum of two layers of ribs oriented to enhance planar flow. Geonets are approximately $^1/_4$ in. thick, and the structure of the net can provide the same planar flow capacity as a 12-in. layer of sand having a permeability of 10^{-2} cm/sec (Richardson, 1994). Geonets have less hydraulic storage than conventional sand or gravel drains; this allows draining fluid to reach a monitoring and recovery point faster. Sand and gravel drainage layers can store a significant volume of water in their pore spaces. The thin geonets have almost no storage capacity, and liquid must be removed continuously, typically by a gravity drain.

Leak Detection

Leak detection systems for tailings impoundments have become commonplace at most metal mines and are required in Washington by RCW 78.56.100. Detection methods vary widely and may include monitoring wells, lysimeters, piezometers, neutron probes, dielectric probes, tracers, and underdrains that route leaking solution to a single point.

One of the newer methods of leak detection uses direct-current electrical resistivity. To locate leaks, an electrical current is generated and sent to the ground between two electrodes, one above the liner and the other in the soil or material below the liner. (A grid of electrodes is also effective.) If the geomembrane is intact, very little electrical current will flow through the highly resistive plastic liner. If a hole exists in the liner, there will be an increase in the electrical current flow at the point of leakage, which will create an anomaly in the electric potential measurements (Bishop, 1997)

WATER QUALITY AND GEOCHEMISTRY

The primary water-quality issue associated with tailings is the potential for toxicity to humans, wildlife, and vegetation through degradation of surface water and ground water by solutions draining from the tailings. One source of toxicity is processing chemicals introduced during milling. Many mills employ cyanide leach processing in metal recovery. Although cyanide is toxic, it degrades quickly under oxidizing conditions. Some degradation byproducts, such as ammonia, are also potentially toxic, depending on the concentration and dose. Most operations employ an inline cyanide destruction circuit before the tailings are discharged to the impoundment facility. In many instances, the level of toxicity introduced by mill process circuits could be largely managed in the mill; this would cut costs and contribute to the goal of economic recovery of minerals. Pollution prevention involves using substitutes for toxic chemicals, reducing the amount or concentration of toxic chemicals used in processing, modifying processes, and improving housekeeping and maintenance (USEPA, 1995).

Another source of waterborne toxicity is the generation and release of acid rock drainage (ARD) from the tailings. Acid drainage results from the exposure of pyrite (FeS_2) and other metal sulfides to air, which causes oxidation and generation of acids and dissolution of metals mobilized by percolating water. Tailings that contain sulfides and insufficient buffering minerals are particularly susceptible to acid generation because finely ground material has a large available reactive surface area. Commonly, older mines deposited tailings in valleys (Fig. 4) or on slopes without designed embankments; at times tailings were dumped directly into streams, rivers, or lakes. Some modern tailings impoundment failures have resulted in uncontrolled discharges and released ARD and tailings materials (Steffen, Robertson, and Kirsten, 1989).

Figure 4. Copper mine tailings in the valley of Railroad Creek above Lake Chelan, Wash. Tailings from the Holden mine were deposited in the valley bottom in the 1940s and 1950s. The tailings have generated acid rock drainage and have also been eroded by the stream and interacted with ground water beneath the tailings. The Washington Department of Ecology, U.S. Forest Service, U.S. Environmental Protection Agency, and Alumet, the parent company of Howe Sound Mining Company that originally mined at Holden, are now cleaning up the site. Because no vegetation was established, blowing dust was a chronic problem. A gravel cover has now stabilized the surface, and revegetation may be easier. Test plots showed that revegetation is possible on these acidic tailings; lupine and Sitka alder, plants native to the area and nitrogen fixers, were the most successful plants in the test plots monitored by the Forest Service (Scherer and others, 1996). (Photo by Eric Schuster, Washington Department of Natural Resources.)

Mitigation of ARD is difficult and expensive. The greatest concern of regulatory agencies is that they will discover ARD after mine closure and abandonment when financial resources to fund mitigation are no longer available. At some mines, the buffering potential of tailings is chemically "used up" years after the tailings have been deposited, resulting in ARD. For example, at the Thompson Creek mine in Idaho, it took about 10 years after deposition for the tailings to generate ARD (Jerry West, Idaho Dept. of Environmental Quality, oral commun., 1998). Thorough study and laboratory testing of the acid generation and neutralization potential of the tailings are imperative if planning and design are to anticipate the ARD issue and avoid buffer depletion.

Current mining and regulatory objectives are to perform some level of investigation of the potential for acid generation before, during, and after mining. Pre-mining investigations should include multiple geochemical tests of the material expected to be placed in the tailings disposal facility. If these conservative tests suggest potential for ARD generation in the tailings, mitigating measures must be included in the milling circuit (for example, a system that removes sulfides) or the TDF design. If there is an ARD potential, regulators should anticipate the need for an engineered design that assures that long-term water quality will not be adversely impacted by discharges from the TDF. The engineered design should include not only containment and isolation of the tailings, but also a reliable method of treating post-closure water discharges. The mining company should estimate the costs involved in treatment facility design, construction, and maintenance. Innovative reclamation might include designs that will minimize oxygen diffusion and percolating water in the tailings.

Adequate baseline water-quality monitoring, including sampling of adits and pits near the site, is a critical element in mine planning. This information can supplement geological studies and predictive geochemical results. The mining company might construct a geological model of the area to explain observed variations in water chemistry and to estimate relative quantities of potentially acid-generating and acid-neutralizing rock. However, the duration of some tests may limit their accuracy in predicting the potential for ARD using various geochemical tests. Short-term tests are likely to be poor predictors of long-term geochemistry and can hamper attempts to quantitatively forecast impacts and costs. The test results resemble meteorological predictions in that, given certain conditions, one can only say that there is a higher or lower probability of acidic or alkaline water (Kleinmann, 1997).

Mine operators routinely analyze rock samples from the mine/prospect site to determine their acid- and alkaline-producing potential on the basis of percent sulfur or pyrite (Kleinmann, 1997). Valuable information can be gained by investigating nearby operations or abandoned mines if they are reasonable analogs of the proposed mine site. If nearby sites are acid-producing, the mining company should conduct intensive geochemical investigations during pre-mine planning as well as during mining and reclamation of the new site. The analytical methods commonly employed to predict ARD fall into the category of static or kinetic tests; those recommended by Price (1997) and Price and others (1997b) for a metal leaching/ARD prediction program are:

Static tests

- trace-element content (total and soluble concentration)
- acid-base accounting
- total-sulfur and amount of sulfate and sulfide
- bulk neutralization potential
- carbonate neutralization potential

- pH
- mineralogy and other geological properties
- petrographic examination

Kinetic tests of reaction rates and drainage chemistry

- pre- and post-weathering characterization
- humidity cell
- on-site pilot tests of tailings
- mine wall washing stations (performed in-place on the rock face)
- site drainage monitoring

The recommended kinetic test is the humidity cell, used for predicting primary reaction rates under aerobic weathering conditions (Price and others, 1997a). In theory, kinetic tests reflect the difference in rates of sulfide oxidation and of calcium carbonate dissolution reactions. Whether this makes kinetic tests more realistic is difficult to say, due to general lack of field verification. In contrast, static tests only indicate relative chemical activity among minerals but are not time dependent. An additional problem shared by static and kinetic tests is that their relevance is limited by the degree to which the samples being tested are truly representative of the mine or waste compositions (Kleinmann, 1997). In the case of tailings, representative samples are generally easier to obtain because ores are blended during grinding and milling.

However, Price and others (1997b) suggest the following factors should be considered when predicting the future drainage chemistry of tailings:

- The composition of tailings may change considerably over time. Milling procedures used by metal mines can remove sulfides and add alkalinity, both of which reduce the metal leaching/ARD potential. However, other milling practices can increase the potential for metal leaching/ARD by adding metal-bearing reagents like copper sulfate. The metal leaching potential will depend on the mill process, pertinent mineralogy of the ore, and particle size.
- Tailings have fine grain sizes and thus have a large surface area; all mineral components are readily available to weathering processes.
- Fine tailings have a reduced pore size and thus lower permeability for both air and water. Restricted air movement may limit the rate of oxygen replenishment, thereby reducing acid generation and metal leaching and perhaps changing the balance between acid generation and neutralization.
- Significant mineralogical and particle-size segregation may occur when tailings are deposited. Selective deposition of heavy minerals may create zones that have higher metal-leaching potential and are close to the deposition point. Separation of sulfides or carbonates on tailings beaches may result in localized ARD.

Specific needs in designing tailings disposal are:

- a milling and metallurgical study of how to remove sulfides and add alkalinity and of the effects of adding or removing metals to determine the effect of these tactics on the metal leaching and ARD potential, and
- regular operational sampling and analysis of tailings to confirm pre-mining material characterization.

The study should cover the range in ore composition and identify the milling process, pertinent mineralogy, and particle size that most effectively eliminates or minimizes ARD.

In tailings, which tend to be more homogenous than waste-rock dumps, predictions of water quality tend to be more reliable. At 16 sites studied by Environment Canada, no site with a calculated excess neutralization potential produced acidic drainage (Kleinmann, 1997).

DISPOSAL METHODS

Tailings are conventionally deposited as a slurry moved in a pipeline (by gravity or pumping) and delivered to a fixed or moveable single point in an engineered surface impoundment (Fig. 5). This process can place the tailings in fairly thick layers and, while excess water is typically decanted from the surface, tailings can remain saturated for years if not dried before new layers are deposited. Reclamation must wait for the surface layer to dry enough to safely support earthmoving equipment (Fig 6). Lower layers either remain saturated or eventually drain out the bottom of the impoundment.

While deposition as a slurry directly to an impoundment is still the predominant method of tailings disposal, modified slurry methods or several other techniques are gaining acceptance and becoming more widely used. These include dewatering, paste, and air-dried deposition. Under some circumstances, these alternative methods result in higher quality and less costly reclamation as well as greater mine efficiency.

Figure 5. Discharge pipes at the Chimney Creek gold mine, Nev., deposit a slurry of saturated tailings. This mine air dries tailings before additional tailings are deposited. The pipe is approximately 6 in. in diameter. (Photo by Allen Throop, Oregon Department of Geology and Mineral Industries).

High-quality reclamation depends on key engineering techniques such as good dam integrity, covers that are nontoxic, and permanent vegetation, all of which result in water quality that is appropriate to beneficial post-mining uses. Options other than conventional slurry deposition that allow for earlier and better reclamation must be considered, especially if they result in less impact to the environment by lowering the potential for release of metals to ground or surface waters. Today, alternative disposal methods are drained and air-dried, submarine, thickened, and paste.

Drained and Air-Dried Method

Mining companies use drained and air-dried (subaerial) methods extensively in arid environments such as Nevada. The method involves sequencing the deposition of thin (<4 in.) lifts of tailings in segments of the impoundment so as to allow previously deposited lifts to dry and consolidate (Knight-Piesold Co, oral commun., 1998). These impoundments must have enough surface area to allow time for drying in one or more parts while deposition continues in other parts; tailings must be deposited over at least two segments for this method to be successful, and as many as 28 segments have been used. The selection of number of segments is based on the climate, tailing production rate, tailing drying characteristics, and facility shape (Gipson, 1998).

In arid climates, desiccation proceeds under high evaporation rates. This reduces the moisture content of the material, while increasing the density and shear strength. Drying allows a fairly strong crust to form, but this crust may crack as a result of shrinking (Newson and others, 1997).

The drained and air-dried method offers the advantages of improving control of the amount and chemistry of the solution within the facility and developing a stable, denser tailings deposit that has a lower moisture content. The tailings are easier to reclaim because they are not saturated and loose. The increase in density resulting from drained and air-dried deposition permits nearly twice the amount of tailings to be stored in the same volume of tailings facility as an undried slurry (Gipson, 1998). Some companies using this method are Battle Mountain Gold Corp. (San Luis mine, Colo.) and American Barrick Resources Corp. (North Block tailings facility, Twin Creek mine, Nev.). (See also Fig. 5.)

Figure 6. The tailings impoundment at Cannon mine near Wenatchee, Wash., in 1994. Temporary roads on a geotextile base and sand over saturated tailings (center left and center right of the photo) allow access to drilling sites to help evaluate tailings chemistry.

Submarine Tailings Disposal

Tailings have been placed via discharge of a slurry at a submerged outfall in lakes and marine water typically more than 150 ft deep. One objective of this disposal method is to place tailings where ambient dissolved oxygen concentrations are minimal, thus reducing the potential for metals to be oxidized, mobilized into the water column and made biologically available, or transported away from the site of deposition. Other objectives are to place tailings in a stable environment and to prevent fines from entering the shallow, biologically productive euphotic zone (Rankin and others, 1997).

Examples of submarine tailings disposal operations are the BHP Island Copper Mine at Rupert Inlet, B.C.; Kitsaoult Molybdenum Mine at Alice Arm, B.C.; Black Angel lead-zinc mine at Maarmolik, Greenland; and Misima gold-silver mine in Papua New Guinea (Rankin and others, 1997). Mine operators believe that submarine disposal is an ecologically acceptable alternative to land-based tailings disposal. Environment Canada and Canada's Department of Fisheries and Oceans have initiated a review of the ecological issues (Rankin and others, 1997).

However, it is not likely that submarine tailings disposal would be used in Washington as this is not allowed by either federal or state law. Thresholds for metal content would probably exceed those allowed by current regulations. Additionally, Department of Natural Resources Aquatic Resources Division regulations (Washington Administrative Code 332-30-166 (1)) regarding submarine disposal state "Open water disposal sites are established primarily for the disposal of dredged material obtained from marine or fresh waters. These sites are generally not available for disposal of material derived from upland or dryland excavation except when such material would enhance the aquatic habitat."

Thickened Tailings

Dry tailings, also called dewatered tailings, may not require a tailings impoundment. This method uses either a filter or a high-density thickener that relies on flocculation. Typical operations use a thickener and filter (such as a belt press) in combination or, increasingly, a thickener alone to produce a tailings consistency similar to a paste. Some mines use cyclones, belt filters, or other mechanical filter equipment alone to reduce moisture content in the tailings. Solids contents as high as 85 percent can be obtained from such devices (Johnson, 1997).

Each 6-in. layer of processed tailings is allowed to dry further prior to adding the next layer. Typically, the layers crack during drying, and the next layer fills the cracks and adds to the pile. Currently, dry stacking operations create high-slump[1], low-viscosity tailings that will flow easily as a thin layer over a wide area (Schoenbrunn and Laros, 1997).

[1] The standard slump test is described in ASTM C143. Slump is defined as the height lost when a filled cone 12 in. tall, 8 in. wide at the base, and 4 in. wide at the top is slowly lifted off a plate and the cone contents are allowed to "slump". A 7-in. slump = the initial 12 in. height – 5 in. height lost.

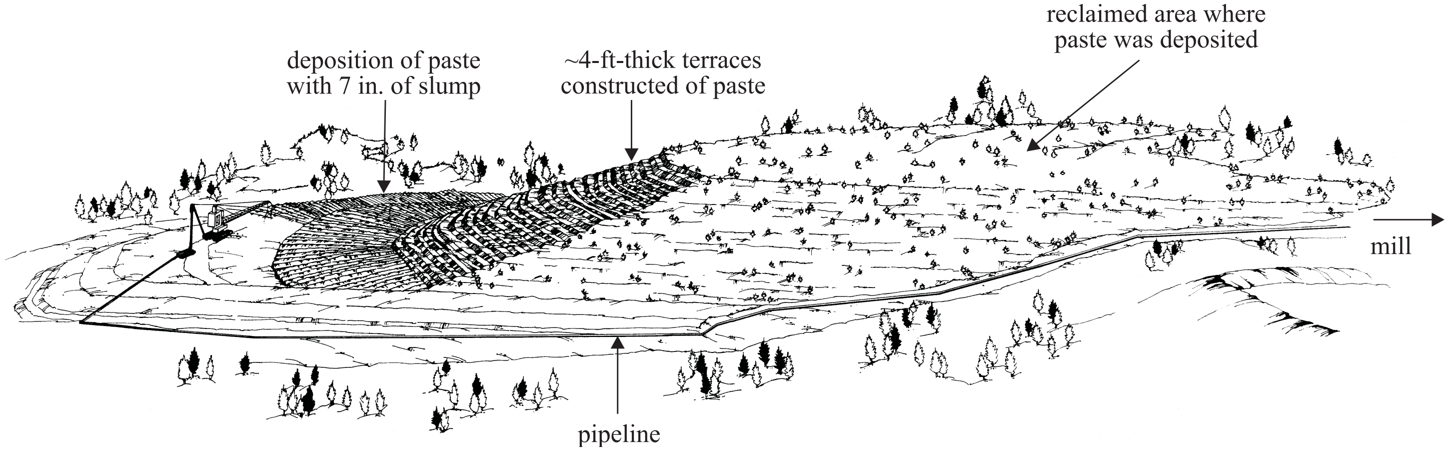

Figure 7. Sketch of a proposed method of paste disposal at ASARCO's Rock Creek project in Noxon, Mont., that will use a paste stacker to construct semicircular windrows (left side of the figure). Each lift (terrace) would be about 4 ft thick and allow for concurrent reclamation shown at the right of the figure. (Modified with permission from Golder Associates, 1996.)

Examples of thickened tailings are at alumina plants such as Alunorte in Brazil, Alcoa of Australia's plants at Pinjarra, Kwinana, and Wagerup, and Alcan's plants in Jamaica, at Vaudreuil in Canada, and at Aughinish, Ireland. Placer Dome's La Coipa mine in Chile uses horizontal belt filters to create thickened tailings. After their tailings pond filled up, the Sunshine gold mine in Nevada used a beltpress in conjunction with a thickener to create space for tailings from remaining ore reserves rather than add a lift to the dam (Schoenbrunn and Laros, 1997)

Paste

Recent developments in dewatering equipment design have made practical the consistent production of tailings that have a low moisture content and distinct flow and water retention properties; these are commonly referred to as pastes. Pastes are dense, viscous mixtures of tailings and water that, unlike slurries, do not segregate when allowed to rest. Generally speaking, pastes resemble wet stiff concrete, and an optimum consistency for a typical paste would be in the range of a 7-in. slump. Terminology for concrete tests is used in the evaluation of pastes. Pastes consist of enough fine particles (at least 15% by weight passing the 20-micron size sieve) to allow them to flow through a pipe, yet have enough retained water to create a nonsegregating mixture. However, the most important aspect of paste is that the largest portion of the entrained moisture is held by surface tension in the fine particle matrix. This phenomenon produces a material that has an initial moisture content in the range of 20 percent (by weight) and, like concrete, a noticeable lack of free-draining water (Cincilla and others, 1997; Golder Associates, 1996)

Pastes have distinct environmental advantages. First, very little free water is available to generate a leachate that might have detrimental effects on ground water. At some sites, eliminating free water during deposition could remove the need for an engineered water-retaining structure. Second, because it does not segregate, it can be pumped to a placement site. In addition, a few percent of portland cement or fly ash can be added to paste; this significantly increases its dry strength, durability, and ability to buffer acid tailings and can encapsulate particles that are potentially acid generating.

Surface paste disposal at the proposed Rock Creek copper mine project (currently in environmental review) at Noxon, Mont. (Fig. 7), would allow ASARCO to reclaim the tailings concurrently with mining (Young, 1997). Among the cited advantages of using paste for this project would be limiting the active areas of disturbance and eliminating the need for a surface water-impoundment, and thereby the potential for seepage through the deposit. The potential for earthquake-induced liquefaction would be low due to the low moisture content of the deposit. Because of the high density achievable with pastes, both the height and footprint of the TDF can be reduced for the same tonnage of tailings. Most significant, however, would be that final closure and return of the property to appropriate post-mining land use could occur shortly after paste production ceases (Golder Associates, 1996).

Pastes have been used extensively as backfill for underground mines. There is now interest in the potential of paste as an alternative to more traditional slurry tailings disposal methods (Cincilla and others, 1997; Golder Associates, 1996). Most rock types are amenable to paste production for surface disposal but may not be suitable for underground backfill. For example, high-sulfide content tailings with portland cement added have been used for underground backfill in Quebec to reduce the volume of surface tailings, strengthen underground workings, and minimize subsidence. But reaction between pyrite and free calcium ions produced by the dissolution of unstable portlandite hydrate ($Ca(OH)_2$) can result in the precipitation of swelling secondary gypsum ($CaSO_4{\cdot}2H_2O$) and very expansive ettringite ($Ca_6Al_2[(OH_{12})](SO_4)_3\ (OH)_{12}{\cdot}26H_2O$), which produces a weak mortar not suitable for backfill (Ouellet and others, 1998). However, acid generation is probably less likely to occur in paste tailings because permeability is decreased and less oxygen can reach the minerals.

RECLAMATION AND CLOSURE

Dewatering and Shaping

Before beginning final closure and reclamation of a tailings facility where the slurry method was used, mine operators commonly must remove the water standing on the tailings (Fig. 8). Reclamation of saturated tailings can be difficult and costly. Final reclamation may have to be delayed until tailings have adequately dried (Fig. 9). An alternative method to surface air drying is the removal of pore water through vertical wick drains. These wick drains give pore water a fast path to the surface. Once drying has proceeded enough for equipment to work on the tailings surface, reshaping develops the planned drainage. Generally, drainage of the tailings should be coupled with control of storm water.

Covers

Cover designs depend on site-specific evaluations. Designing one cover that would be suitable for all tailings is not possible because of the wide range of climate, soil, and topographic conditions at mines (Ritcey, 1989).

Covers for tailings are generally either vegetation or a layer of soil, rock, or water. Under some circumstances abandoned tailings can be revegetated without applying topsoil. Abandoned mine tailings at Telluride, Colo., were revegetated by simply tilling organic amendments (manure and hay) and inorganic fertilizer into the surface (Redente and Baker, 1996). In virtually all instances, salvaging and replacing soil at operating mines would be less costly than amending tailings. For some abandoned tailings, the simplest covers used to stabilize the surface have been single or multiple layers of gravel. Where water layers have been used, no vegetation was established. Miners in British Columbia have used a layer of water to reduce the amount of oxygen entering highly acidic tailings.

Other cover designs have incorporated a gravel layer for drainage or a capillary break below the topsoil. Multilayer covers might consist of a top-to-bottom sequence of soil and gravel, infiltration barriers such as a geomembrane or a clay layer, and a geotextile (if required for support during construction). The U.S. Environmental Protection Agency (1989) recommends a multiple layer cover for hazardous waste such as uranium tailings.

Some tailings covers incorporate a barrier to prevent plant roots or animals from disrupting the integrity of the drainage and infiltration layers and burrowing animals from bringing contaminants to the surface. Typical biointrusion barriers are layers of cobbles or coarse gravel placed between the top layer and the waste (and infiltration barrier if present). This biointrusion layer can also be separated from soil by a geosynthetic filter layer (Henderson and others, 1992).

Mining companies have tried biointrusion barriers throughout the world for many types of hazardous wastes, mostly those associated with radioactive material. Bowerman and Redente (in press) evaluated studies documenting root intrusion where barriers had been emplaced. They conclude the ability of many kinds of barriers to protect against intrusion is questionable. For example, several plant species (such as crested wheatgrass, big sagebrush, and saltcedar) penetrated these barriers in moderately damp to arid environments. Harvester ants also managed to invade waste through gravel barriers. Mice, kangaroo rats, pocket gophers, and prairie dogs also breached the integrity of protective barriers.

At their Midnite uranium mine near Ford in northeastern Washington, Dawn Mining Company proposes a 15.3-ft-thick homogenous cover of sandy soil to protect water quality and control radon emanation. The site is characterized by sandy and sandy loam soil. Ponderosa pine woodland is the local late-successional native vegetation. The pines are 40 to 60 ft tall at the Midnite mine and can produce roots that reach depths

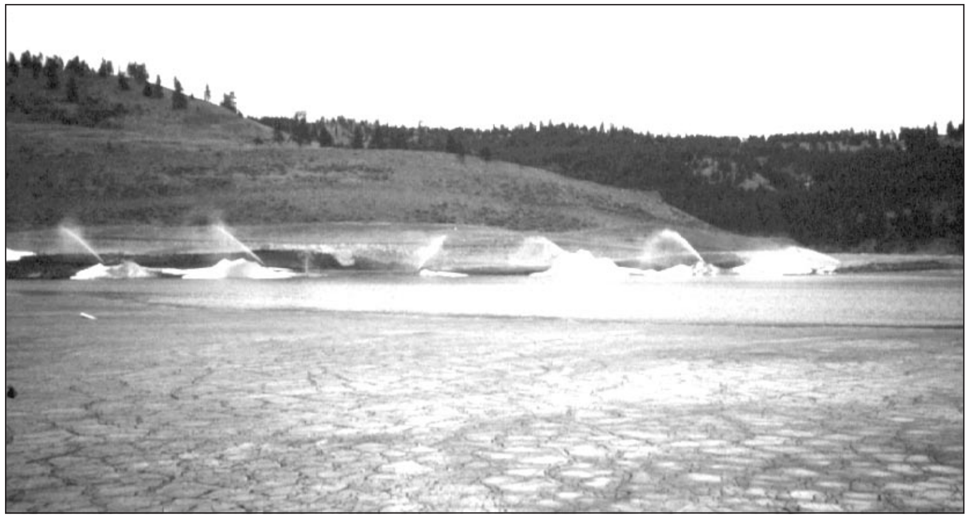

Figure 8. Hecla's Republic Unit tailings impoundment at Republic, Wash., where water is evaporating from the tailings surface prior to reclamation. The company pumped water ponded on the surface though sprinklers to speed evaporation, thereby drying the tailings. White piles in the center of the photo are ice formed around the sprinklers during the winter of 1995 operation. In the foreground, the tailings have begun to dry, and mudcracks have formed.

Figure 9. Cannon mine tailings undergoing final reclamation in 1996 after 2 years of drying. Here a woven polypropylene fabric geotextile layer was laid down first as a supportive base on which to place sand and soil. A lower cover layer of 2.5 ft of gravelly sand was covered by an upper layer consisting of 2 ft of sandy silt pushed out onto the surface by small bulldozers. The surface was then prepared for revegetation by scarifying. Reseeding occurred the following fall and winter, and grasses are thriving. (See also Figs. 3 and 6.) (Photo courtesy of Asamera Minerals.)

as great as 75 ft, although much shallower rooting is common; company consultants found roots below 8 ft at the mine and below 10 ft at a nearby site. Other plants native to the area are bluebunch wheatgrass and needle-and-thread, both perennial grass. Bluebunch wheatgrass rooting to 4.5 ft has been reported, and needle-and-thread roots reach deeper than 6 ft (McLendon and others, 1997). The tailings cover design is intended to accommodate the expected final native plant community. The mining company and their consultants believe that the noncohesive sandy soils will allow for self-healing of root holes (left after roots have rotted), thereby addressing biointrusion concerns (McLendon and others, 1997).

Capillary Barriers

Capillary barriers of fine soil over coarse soil can be a simple, low-cost method of effectively limiting water and oxygen movement through the tailings cover (Stormont and others, 1996). In many settings, the capillary barrier functions as the drainage layer as well (Henderson and others, 1992). Capillary forces hold the water in the fine layer until it is removed by evapotranspiration or drains where the fine-coarse interface is sloped. A capillary barrier is effective if the combined effects of evaporation, transpiration, and lateral diversion exceed the infiltration from precipitation. However, if the fine layer becomes saturated, capillary forces will decrease and water will drain quickly through the fine layer into the coarse layer. Design considerations are unique to each site and must account for seasonality of precipitation and evapotranspiration.

REVEGETATION

Revegetation success generally depends on the cover design and tailings chemistry. For vegetation to be effective and healthy, the roots should be able to penetrate the soil and reach enough water that contains adequate nutrients and no toxic components. Metalliferous mine tailings commonly contain low concentrations of essential plant nutrients; nitrogen levels are invariably inadequate for plant growth (Williamson and others, 1982). Mining companies must conduct tests prior to and during mining to investigate the physical and chemical nature of the tailings and to determine if vegetation can be reestablished. Important considerations are temperature, precipitation, wind, and aspect, as well as texture of the tailings.

Direct revegetation of tailings without soils can be extremely difficult. An improved seedbed encourages germination and establishment of vegetation. Establishing vegetation on neutral tailings is less difficult than on nutrient-poor, salt-rich or alkaline or acid tailings. Over any acid-generating tailings, the soil layer, which is in many places topsoil and a mixture of subsoils, must be thick enough to prevent salt or acid migration to the surface. Acid tailings without soil coverings must be leached before seeding (Munshower, 1994). It may also be necessary to apply lime or some other neutralizing materials, as well as amendments such as manure, wood chips, compost, or biosolids.

Incorporating compost or biosolids and industrial wastes, such as fly ash, into acid-generating (or potentially acid-generating) tailings and mine waste has been effective. In Pennsylvania, for example, miners used coal fly ash to neutralize acid mine wastes and allow vegetation to be established (Scheetz and others, 1998).

In Washington, RCW 78.44 has required topsoil salvage only since 1993. It states "'Topsoil' means the naturally occurring upper part of a soil profile, including the soil horizon that is rich in humus and capable of supporting vegetation together with other sediments within four vertical feet of the ground surface." This definition indicates that mine operators have to salvage more than just the "A" horizon for reclamation. If topsoil or amendments such as hay, biosolids, paper residues, or compost are available, revegetation of mine tailings is generally not a problem. Permanent stabilization of acid-generating tailings that are covered with a cap to establish a nontoxic rootzone can be accomplished with normal agricultural practices of seedbed preparation, fertilization, and seeding.

With a proper seed mix and soils amended with paper waste, which is widely available in the Pacific Northwest and other parts of the country, a lasting vegetative cover can be quickly established with little or no additional fertilizer application. Paper mill waste can act as both an amendment and a capillary barrier. Some of the advantages of paper mill residuals are low permeability, high water-holding capacity, low erodibility due to its fibrous nature, structure and stability suitable for root development, and neutral to basic pH to buffer infiltrating water before it reaches acid tailings. Canadian mining companies have successfully used paper pulp waste, a spongy, partially saturated material that absorbs large quantities of water, as a soil amendment for reclamation (Cabral and others, 1997, 1998). Paper mill sludges are composed of 40 to 60 percent organic material and have been "recycled" for successful use as landfill caps at several sites (Moo-Young and Zimmie, 1995; Maltby and Eppstein, 1996; McGee and others, 1996).

At the East Sullivan gold-bearing massive sulfide mine in Val d'Or, Quebec, a 6.4-ft-thick cover of softwood and hardwood bark over acid-generating tailings effectively prevents oxygen from reaching the tailings. Biosolids from a municipal water treatment plant tilled into the first foot of the bark add nutrients (Tremblay, 1994). This site now supports a dense grass cover.

Re-establishing native plants at mine sites has become an important objective for reclamation. In many places, desired post-reclamation plant communities composed of native plant species are preferred because most are adapted to the climate and elevation of the site. Some native plants can out-compete some introduced (exotic) species over time and are more useful to wildlife. The vegetation at or surrounding the mine site can be used as a guide to selecting native species. Using native seed mixes or plants produced from locally collected seeds and cuttings and locally transplanted plants can greatly accelerate revegetation. If preplanning is sufficient and the appropriate tailings deposition methods selected, soil and native vegetation can be transferred directly from areas being stripped for mining to the TDF. This approach is less expensive and typically more successful than long-term soil storage. Soil hauled directly from a newly stripped area to a reclamation area carries with it viable seeds of native vegetation that can rapidly establish on the reclaimed area. This typically reduces the need for added seed and plant material (Norman and others, 1996). This method would be most appropriate at mines using paste deposition and concurrent reclamation.

Using Cattle as a Technique for Establishing Revegetation

At a mine at Miami, Ariz., miners have tried an innovative method of establishing vegetation on tailings (A. Throop, Oregon Department of Geology and Mineral Industries, written commun., 1996) (Fig. 10A,B). Where importing topsoil, seeding, fertilizing, and irrigating had failed, penning cattle on the tailings piles was successful in encouraging vegetation. Generally, cattle trample and kill vegetation. In this case, the cattle trampled hay mulch, urine, and manure deep into the tailings and created terraces by their network of trails on the steep slopes. When compared to cattle not on tailings, the blood and tissue of these animals showed no toxic or unusual concentrations of trace elements (Dagget, 1997).

Coarse Woody Debris

Mining companies and regulatory agencies recognize the importance of replacing coarse woody debris on reclaimed areas (Harmon and others, 1986). At mine sites in the Pacific Northwest coarse woody debris is now incorporated in final reclamation. For example, a recently proposed mine will re-place stockpiled woody debris at approximately 7 tons per acre to provide a substrate for essential microorganisms. The company will salvage logs ranging from 10 to 24 in. diameter at their small end and at a variety of lengths longer than 6 ft. Furthermore, salvaged lichen-encrusted rock randomly distributed across the reclaimed areas will promote colonization by lichen (Battle Mountain Gold Co. and Golder Associates, 1998).

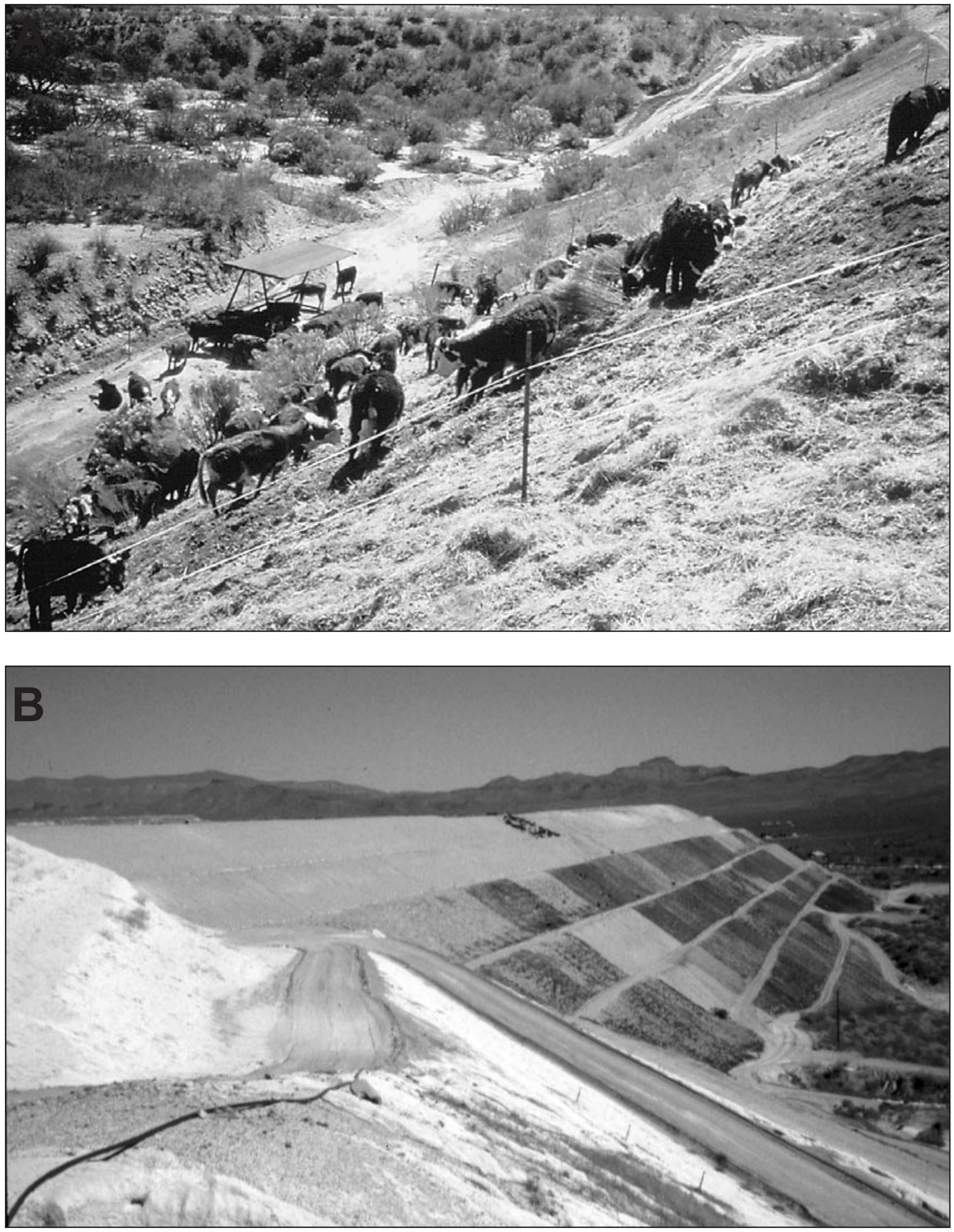

Figure 10. **A.** Penned cattle being fed at tailings piles at the Miami, Ariz., copper mine. The trampling helped to establish vegetation where several other methods of reclamation had failed. **B.** Lower benches of Miami copper mine tailings were reclaimed using penned cattle. Upper benches have not been reclaimed. The face shown is about 3/4 mi long and 600 ft high and has a slope of 2 horizontal to 1 vertical. The footprint of this tailings impoundment is about 1,100 acres. The benches are 50 ft apart vertically, and interbench slopes are 1.3 horizontal to 1 vertical. (Photos by Allen Throop, Oregon Department of Geology and Mineral Industries.)

CONSTRUCTED WETLANDS

Wetlands are an effective means of improving water quality; coal mines in the eastern U.S. were the first to use wetlands in this context. Passive water treatment using constructed wetlands essentially simulates natural processes and is being used more commonly to treat mine water (Fig. 11). Bacterial reduction of sulfate and iron and precipitation of metal sulfides are important chemical processes in passive anaerobic treatment. Sulfide precipitates accumulate in the anaerobic zone and are not carried in the effluent (Filipek, 1997; Filipek and others, 1992; Sengupta, 1993). In a surface-flow aerobic wetland used to treat acid drainage, the dominant process is oxidation of iron and precipitation of iron hydroxides. Water in aerobic wetlands must be sufficiently alkaline to keep pH from falling as a result of the hydrolysis of iron. An anoxic limestone drain can be installed before water enters the wetland to add alkalinity and raise pH if no iron is present in the initial drainage (Filipek, 1997; Brodie, 1991). This type of wetland treatment works best if heavy metal concentrations are low.

TRENDS

Because mine operators and agencies now have a better understanding of the physical function of tailings and have improved techniques to reclaim them, tailings have become less problematic. However, tailings impoundments will require long-term monitoring to verify that they are not a source of contaminants.

Among recent trends in dealing with tailings are:

- Regulatory controls are becoming more stringent, and mine operators are expected to rigidly adhere to them. Example of such control are Washington's Metal

Mining and Milling Act (RCW 78.56) and Oregon's Chemical Process Mining Act (ORS 517.952).

- Dry tailings deposition systems, such as dewatered, paste, or air-dried tailings, are reducing management problems.
- There is much wider recognition that intense geochemical testing early in mine planning is necessary to characterize tailings chemistry and to plan environmentally sound deposition.
- To achieve long-term physical stability of the impoundment, proper designs for closure more commonly consider long-term storm-water retention and seismic stability.
- An increased use of non-acid-generating waste materials for construction of mine facilities is reducing both disturbed areas and costs.
- Mine companies attempt to reduce cyanide levels to the lowest concentration consistent with technical feasibility and reliability to protect human health and wildlife.
- Contaminant monitoring programs and response plans are more widely required.
- Geosynthetic and clay liners have become widely accepted and are commonly used.
- Topsoil salvage and revegetation of tailings has become the norm.

Figure 11. Wetlands being constructed at the base of the Cannon mine (Wenatchee, Wash.) tailings impoundment. Although water discharged from the underdrain beneath the tailings is not acidic, these aerobic wetlands are being used to improve and maintain water quality. They were built as a hedge against future water degradation predicted on the basis of tailings pore-water studies conducted during closure. The inlet for the wetland is the lower left of the photo near the building. After water leaves the wetland, it infiltrates into the ground.

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BOOK REVIEW: West Coast Fossils—A guide to the ancient life of Vancouver Island

by Rolf Ludvigsen and Graham Beard
Harbour Publishing
Box 219, Madeira Park, BC V0N 2H0
1997 (revised edition), 216 p.
Paperback, $18.95 U.S. and Canadian

The many fans of the first edition of this fine guide will be glad to see the additions of major taxa to the record of fossils in an area just to the north of Washington. The preface to this edition indicates that there are now Carboniferous trilobites, a pterosaur, Cretaceous beetles, articulated fish (Triassic), and dinosaurs (a tooth), not to mention Middle Jurassic fossils and significant new finds of Mesozoic plant remains, all identifications vetted by current experts. Interestingly, credit for most of these discoveries goes to amateur paleontologists. And amateurs get thanks for helping save material at a Cretaceous plant locality.

To cover the additions, the book has been expanded to show examples of the new taxa. The many new (and high quality) photos augment the book's clear and helpful information about identification as well as histories of the taxa. The remaining text is verbatim from the earlier edition, just slightly rearranged.

Readers who are not familiar with formation or geographic names can check out the helpful stratigraphic section on p. 43. That will make it clear that it is, for example, Protection Formation at Nanaimo, and Lambert Formation at Collinshaw Point; commas in the captions might help.

This revised edition appears only three years after the first. The authors deserve our thanks for bringing out the important new material so promptly. This book would be an excellent addition to the region's libraries and to personal collections for its educational text as well as inspiration for a trip to Vancouver Island. The generalized geologic maps for the several periods represented on the island should make it possible to develop a rewarding itinerary.

Users of this thoroughly portable and well-designed guide will need little more than patience and sharp eyes to enjoy the hunt. Considering the sizes of some of the new finds, we need to travel with hand lenses at the ready. While the geology of Vancouver Island is not very like that of adjacent Washington, the message is clear: Go look. There is much yet to learn about former life nearly everywhere you go.

Kitty Reed

SUMMER INTERNS

We are fortunate to have two students from Community Youth Services working with us this summer. They have each done an excellent job for us, and we will be sad when their program is finished.

Myhanh Tran is working as a clerical assistant this summer. She was born in Viet Nam, but has lived here for six years. Myhanh will be a senior at North Thurston High School and is interested in the computer field. She plans to attend South Puget Sound Community College and the University of Washington.

MiMi (Melissa) Beach is working part-time in the Geology library and the rest of the time as a clerical assistant. She will be a sophomore at New Century High School. She is very interested in environmental science and hopes to make it a career someday.